Letters to the Editor

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Mobilities of He Ions in Liquid Helium*

LOTHAR MEYER AND F. REIF
Institute for the Study of Metals, University of Chicago, Chicago, Illinois
(Received January 20, 1958)

AN investigation of the motion of microscopic charged particles in He II can be expected to yield interesting information concerning the elementary excitations in this quantum fluid. Recently Careri *et al.* reported some measurements on the heat flush of ions in He.[1] We have made a direct study of the mobilities of positive and negative ions in liquid helium.

Our method is essentially an adaptation of one used for ion mobility studies in gases by Tyndall and Powell.[2] The electrode assembly schematized in Fig. 1 is im-

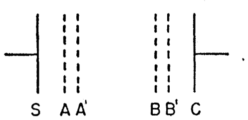

FIG. 1. Schematic diagram of the experimental arrangement. The disk S is plated with Po^{210}. He ions produced near S drift under the influence of an electric field toward the collector C connected to an electrometer. The grid pairs $A\,A'$ and $B\,B'$ have ac potentials applied to them and act as shutters.

mersed in liquid He. Alpha particles, emitted from Po^{210} plated[3] on the disk S, ionize He atoms immediately in front of S. Batteries connected to the various electrodes maintain between them electric fields of appropriate direction to drive ions of the desired sign to the collector C which is connected to an electrometer. The closely spaced pair of grids $A\,A'$, with a superimposed ac electric field of frequency ν applied between them, acts like a shutter allowing ions to pass through predominantly during one particular part of each cycle only. The pair of grids $B\,B'$, with the same ac field applied between them, acts like a second identical shutter. As a result, the number of ions reaching C is a maximum essentially whenever the time t, required for the ions to drift the distance d from A' to B under the influence of the dc electric field E applied between them, is equal to an integral number of periods ν^{-1} of the ac field. An experimental curve of collector current as a function of ν is illustrated in Fig. 2. The separation

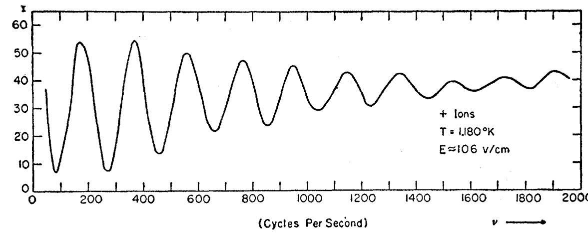

FIG. 2. A typical experimental curve of current I reaching the collector *vs* the frequency ν of the ac field between each shutter. In practice such a curve is traced out on a recording meter connected to the electrometer output while the oscillator frequency is slowly swept by a clock motor.

in frequency ν_0 between any two adjacent maxima or minima on this curve measures t^{-1}. Thence one deduces the drift velocity u in the region $A'\,B$ and the mobility $\mu \equiv u/E$.

The experimental results obtained for the mobilities are shown plotted in Fig. 3. Since the effective value

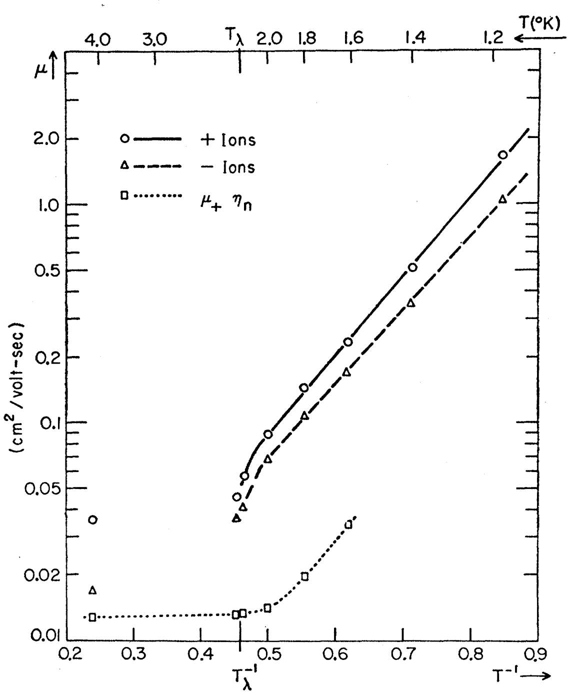

FIG. 3. Logarithmic plot of the mobilities μ of positive and negative ions as a function of T^{-1}. The dotted curve shows the product $\mu_+\eta$ in arbitrary units, η being the viscosity of liquid He. [The temperature-dependent values of η in the He I range are taken from R. D. Taylor and J. G. Dash, Phys. Rev. **106**, 398 (1957). Below the λ point the values of η are the normal fluid viscosities given in reference 7.]

of d is somewhat uncertain because of electrical edge effects near the grids and the finite separation of $A\,A'$ or $B\,B'$, the absolute values of μ are uncertain to within a common scale factor[4] which may differ from unity by as much as perhaps 50%. Except for this scale factor, however, all the values should be good to within 2%. It was verified that u is indeed proportional to E, at least between fields from 50 to 200 v/cm. Within this range of fields, therefore, there is no trace of the marked dependence of mobility on E claimed by Careri *et al.*[1] The ratio μ_-/μ_+ of negative- to positive-ion mobilities is slightly temperature-dependent; e.g., its value decreases from 0.77 at 2°K to 0.62 at 1.18°K. The exact nature of the ions is not known. They may well be complexes more complicated than simple He^+ or He^- ions.[5]

The striking increase of μ with decreasing temperature shown in the logarithmic plot of Fig. 3 suggests the correlation $\mu \sim \rho_n^{-1}$ with the density of the normal fluid. This is what one might expect from a simple model in which the ion mean free path varies inversely with the number of scattering excitations (predominantly rotons above 1°K) where these are not too dense, i.e., at temperatures sufficiently below the λ point. Putting approximately $\rho_n \sim e^{-\Delta/kT}$ for the roton contribution to the normal fluid density[6] in the temperature range of interest, the slope of the μ_+ curve in Fig. 3 yields $\Delta/k = 8.3$°K. This lies within the spread of values for Δ/k deduced from measurements of ρ_n by different methods. Thus oscillating disk techniques yield $\Delta/k = 10.6$°K, whereas the combination of second sound and thermal data gives lower values in the range $\Delta/k = 8$—9.6°K.[7] On the other hand, in He I or just below the λ point where the excitations are very dense, one might expect to be able to consider He like an ordinary liquid. In that case one expects $\mu \sim \eta^{-1}$ on the simple model of a quasi-macroscopic charged sphere being dragged through a medium of viscosity η.[8] The approximate constancy above 2°K of the product $\mu_+\eta$ shown by the dotted curve in Fig. 3 may lend some support to this naive picture.

It is planned to extend these measurements with improved techniques to temperatures below 1°K and to the rotating fluid.

* This work was supported in part by grants from the National Science and the Alfred P. Sloan Foundations.

[1] Careri, Reuss, Scaramuzzi, and Thomson, Proceedings of the Fifth International Conference on Low Temperatures, Madison, Wisconsin, August, 1957 (unpublished), p. 79.

[2] A. M. Tyndall and C. F. Powell, Proc. Roy. Soc. (London) **A129**, 162 (1930).

[3] We are indebted to Dr. J. L. Richmond of the Mound Laboratory, Monsanto Chemical Company, for kindly preparing the Po source for us.

[4] If absolute values of the mobilities were of interest, the scale factor could be determined by making these measurements for two different values of the spacing d between A' and B. The *difference* in drift distance would then be known and unaffected by edge effects near the grids which cancel.

[5] For example, in He gas He_2^+ ions predominate over He^+ ions at the higher pressures [A. V. Phelps and S. C. Brown, Phys. Rev. **86**, 102 (1952)], and have higher mobilities than the latter since they are distinctly different from the neutral atoms and hence do not suffer resonant charge exchange scattering.

[6] I. M. Khalatnikov, Uspekhi Fiz. Nauk S.S.S.R. **59**, 673 (1956).

[7] J. G. Dash and R. D. Taylor, Phys. Rev. **105**, 7 (1957).

[8] J. Frenkel, *Kinetic Theory of Liquids* (Oxford University Press, New York, 1946), p. 193.

21-Centimeter Solid-State Maser*

S. H. Autler† and Nelson McAvoy‡

Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts

(Received February 3, 1958)

A 3-LEVEL solid-state maser[1] using $K_3Co(CN)_6$ doped[2] with $\frac{1}{2}$% $K_3Cr(CN)_6$ has been operated as an amplifier at 1382 Mc/sec. The design is somewhat different from a previously reported one which operates in the same frequency range.[3] Saturating power is supplied at 9070 Mc/sec through a wave guide while a coaxial line terminated in a probe serves as both input and output for the amplified power. The band width has been varied from about 1 Mc/sec to less than 50 kc/sec by changing the probe insertion and thus the external coupling. At an operating temperature of 1.25°K the product of voltage gain and band width is about 1.85×10^6 sec^{-1} over a considerable range.

A means of obtaining a reasonably large filling factor and still saturating all spins is to use a cavity with dimensions small compared to a wavelength at the signal frequency. With a coaxial cavity (Fig. 1) shortened by capacitative loading at one end, a filling factor of approximately 0.5 is obtained. Pumping is possible in several higher-order modes but best results were obtained for the 9070-Mc/sec mode.

The maser operates at a magnetic field of about 1200 gauss, making an angle of 18° with the a axis and 90° with the b axis of the crystal.[2] It can be seen from Fig. 2 of reference 2 that in this region emission can occur between levels 2 and 3 and saturation between 2 and 4, where the levels are designated in order of increasing energy.

It is of some interest that we were unable to make a maser amplifier work using the same cavity and a crystal containing 1% Cr. The reason for this is not yet understood, but a possible explanation is that the additional power required for saturation at the higher concentration raises the lattice temperature, reducing the spin-lattice relaxation time, which results in still greater power requirement for saturation, etc.

The measured gain band width product is less than one-fifth the theoretical value for $\Delta M = \pm 1$ transition.

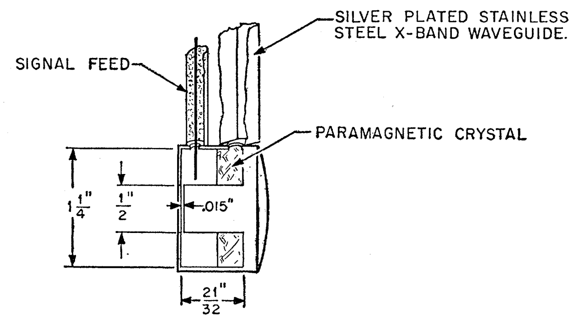

Fig. 1. Cross-sectional view of maser cavity.